SOLAR/1056-79/14

Solar Energy System Performance Evaluation

M. F. SMITH ASSOCIATES
SINGLE-FAMILY RESIDENCE
Jamestown, Rhode Island
October 1978 Through March 1979

U.S. Department of Energy

National Solar Heating and Cooling Demonstration Program

National Solar Data Program

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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

M. F. SMITH ASSOCIATES
JAMESTOWN, RHODE ISLAND

OCTOBER 1978 THROUGH MARCH 1979

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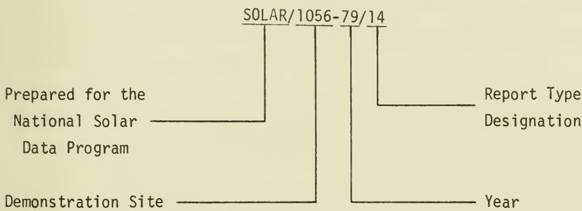
NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under specific format. For example, this report for the M. F. Smith Associates project site is designated as SOLAR/1056-79/14. The elements of this designation are explained in the following illustration.



- o Demonstration Site Number:

  Each project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- o Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).
  - Solar Energy System Performance Evaluations are designated by the number 14.

- Solar Project Descriptions are designated by the number 50.

- Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U. S. Department of Energy Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth to achieve a substantial reduction in nonrenewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines (IBM) Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The Solar Energy System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description and operational characteristics and capabilities. The Monthly Performance Report, which is the basis for the Solar Energy System Performance Evaluation Report, is published on a regular basis. Each parameter presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month

by the National Solar Data Network (NSDN). Documents referenced in this report are listed in Section 6, "References." Numbers shown in brackets refer to reference numbers in Section 6. All other documents issued by the National Solar Data Program for the M. F. Smith Associates solar energy system are listed in Section 7, "Bibliography."

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the M. F. Smith Associates solar energy system. The analysis covers operation of the system from October 1978 through March 1979. The M. F. Smith Associates solar energy system provides domestic hot water and space heating to a single-family residence located in Jamestown, Rhode Island. Section 2 presents a summary of the overall system results. A system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 5 presents a detailed assessment of the individual subsystems applicable to the site.

The measurement data for the reporting period were collected by the NSDN [1]. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

2. SUMMARY AND CONCLUSIONS

This section provides a summary of the performance of the solar energy system installed at M. F. Smith Associates, located in Jamestown, Rhode Island for the period October 1978 through March 1979. This solar energy system is designed to support the domestic hot water and space heating loads. A detailed description of the M. F. Smith Associates solar energy system operation is presented in Section 3.

2.1 Performance Summary

The solar energy site was unoccupied from October 1978 through February 1979, and the solar energy system operated continuously during this reporting period. The total incident solar energy was 113.12 million Btu, of which 36.86 million Btu were collected by the solar energy system. Solar energy satisfied 72 percent of the space heating requirements during the period October 1978 through January 1979. There was no DHW load during this period. The solar energy system provided an electrical savings of 4.78 million Btu during the period October 1978 through January 1979.

During October the measured demand for space heating was satisfied entirely by diverting storage water to the hydronic heating coil, a mode made possible by storage temperatures in excess of 90°F.

In November the first indications of the solar-assisted heat pump inadequacy were noted. There was frequent operation of the heat pump to keep the temperatures in heat zone 1 within the 69°F to 70°F range and temperatures in heat zone 2 within the 63°F to 65°F range. The average ambient temperature during these periods of frequent heat pump operation was usually in the lower 30-degree range.

During December the hydronic coil was not used for space heating because of the low storage temperatures. There was continuous heat pump operation during most of the month to maintain the 67°F average building temperature in a 36°F average ambient temperature.

The drain-down plumbing on the M. F. Smith Associates solar energy system is such that there are lines connecting the collector loop pump outlets through solenoid valves to their respective storage return lines. These provide flow paths in parallel with the collector arrays when the solenoid valves are open. On most days during December, there were indications that during collector loop operation the flow shunted the collectors through the drain-down solenoid valves. The shunting usually occurred for several hours after initiation of collector loop flow. This condition is believed to be caused by set-point problems in the drain-down freeze protection control system which allows the drain-down solenoid valves to be open during some periods of collector loop operation. This condition persisted through the reporting period.

The demand for space heating during January was satisfied by diverting storage water with an average temperature of 46°F to the heat pump. There was heat pump activity during each hour in January to maintain the 65°F average building temperature in a 32°F ambient. There was no indication of the booster unit HR1 operating during January.

During February the solar-assisted heat pump ran almost continuously to provide an average building temperature of 62°F with an average outdoor ambient temperature of 22°F.

During March there were only erratic power indications from the sensor for the DHW recirculation pump. Indications from the DHW recirculation flow sensor were also erratic. The heat load during March was mostly satisfied by the heat pump. However, on a few days the heat load was satisfied by circulation of sclar-heated water directly to the hydronic coil. Auxiliary electrical baseboard heaters were installed during March at which time the house became occupied. The auxiliary heaters were not instrumented during March.

2.2 Conclusions

Continuous operation of the solar-assisted heat pump indicated that the heat pump capacity was inadequate for the heat load during December, January, and February. The operation of the heat pump during March relative to the

February operation was more reasonable. However, a number of factors other than auxiliary electrical baseboard heater usage contributed to the reduction of the solar heat pump activity. There were fewer heating degree days (778 vs 1197 in February), a higher average storage temperature (60°F vs 40°F in February), and a higher average ambient temperature (40°F vs 22°F in February).

The operation of the drain-down control system solenoid valves which allowed the collector flow to frequently shunt the collector array is being investigated. This condition results in less than optimum solar energy being collected and decreased collector array efficiency.

3. SYSTEM DESCRIPTION

M. F. Smith Associates is a single-family residence in Jamestown, Rhode Island. The home has approximately 1752 square feet of conditioned space. Solar energy is used for space heating the home and preheating domestic hot water (DHW). The solar energy system has an array of flat-plate collectors with a gross area of 512 square feet. The array faces 15 degrees west of south at an angle of 45 degrees to the horizontal. Water is the transfer medium that delivers solar energy from the collector array to storage and to the space heating and hot water loads. Solar energy is stored in a 3150-gallon concrete storage tank. City water is preheated in storage and in heat exchanger HW1, which receives energy from a coil at the output of the heat pump compressor. Preheated water is supplied, on demand, to a conventional 82-gallon DHW tank. Solar-heated water from the storage tank is directed to a heat pump or to an hydronic heat exchanger to provide space heating. When the storage water temperature is insufficient to satisfy the heat pump input requirements, an electrical heating element (booster unit HR1) in the line between storage and the heat pump provides auxiliary energy. During the cooling season, heat is removed from the conditioned space and discharged into storage, which should be maintained below 100°F by operating the collector system at night. An electrical heating element in the DHW tank provides auxiliary energy for water heating. The system, shown schematically in Figure 3-1, has three modes of solar operation.

<u>Mode 1 - Collector-to-Storage</u>: This mode activates when the temperature difference between the collectors and the bottom of storage is 20°F or higher. Pumps P1 and P2 circulate water from the storage tank through the collectors and back. Circulation continues until the temperature difference between the collector and storage falls to 5°F or less. If the temperature in a collector panel reaches 45°F, the collector array drains down.

<u>Mode 2 - Storage-to-Space Heating</u>: This mode activates when the manually set thermostat in the conditioned space zones 1 and 2 indicates a demand for heat. Pump P3 circulates water from storage to the heat pump in the energy conservation module (ECM). If the input water temperature is higher than

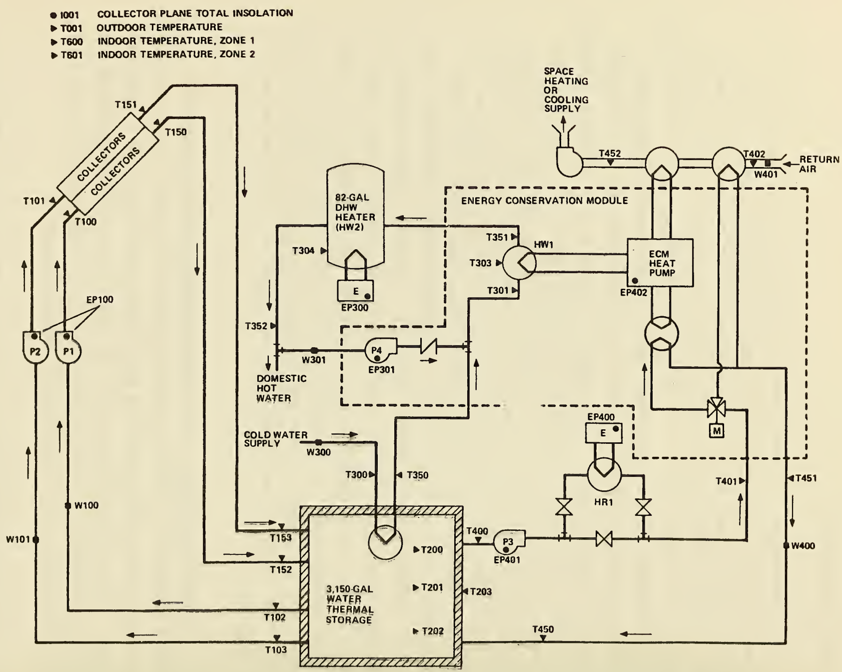


FIGURE 3-1. SOLAR ENERGY SYSTEM SCHEMATIC
M. F. SMITH ASSOCIATES

90°F, the water will be diverted to an hydronic heating coil. If the water temperature is less than 90°F, the water will be diverted to the heat pump.

Mode 3 - DHW Preheating: This mode activates when city water enters a heat exchanger in the storage tank and flows to the HW1 preheater which receives energy from a coil at the output of the heat pump compressor inside the ECM. When there is no draw, the ECM internal pump circulates hot water from HW2 to HW1, as long as HW1 remains hotter than HW2. If a draw occurs, water flows from HW1 to HW2 for a final temperature boost.

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the M. F. Smith Associates solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies. All performance factors and their definitions are listed in Appendix A.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for calculating the daily and monthly performance of each component subsystem. The performance factor equations for this site are listed in Appendix B.

Each month, as appropriate, a summary of overall performance of the M. F. Smith Associates site and a detailed subsystem analysis are published. These monthly reports for the period covered by this Solar Energy System Performance Evaluation (October 1978 through March 1979) are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

In addition, data are included in this report for which monthly reports are not available. This data is included with the intention of making this report as comprehensive as possible. Months for which no published monthly reports exist are shown in parentheses in the tables and figures. In the tables and figures in this report, an asterisk indicates that the value is not available for that month; N.A. indicates that the value is not applicable for this site.

5. PERFORMANCE ASSESSMENT

The performance of the M. F. Smith Associates solar energy system has been evaluated for the October 1978 through March 1979 time period. Two perspectives were taken in this assessment. The first views the overall system in which the total solar energy collected, the system load, the measured values for solar energy used, and system solar fraction are presented. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level as been presented.

The second view presents a more in-depth look at the performance of individual subsystems. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating and domestic hot water (DHW) subsystems. Included in this section are all parameters pertinent to the operation of each individual subsystem.

In addition to the overall system and subsystem analysis, this report also describes the equivalent energy savings contributed by the solar energy system. The overall system and individual subsystem energy savings are presented in Section 5.5.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

5.1 Weather Conditions

Monthly values of the total solar energy incident in the plane of the collector array and the average outdoor temperature measured at the M. F. Smith

Associates site during the reporting period are presented in Table 5-1. Also presented in Table 5-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from <u>Reference Monthly Environmental Data for Systems in the National Solar Data Network</u> [4]. A complete yearly listing of these values for the site is given in Appendix C.

During the October 1978 through March 1979 period the average daily total incident solar energy on the collector array was 1216 Btu per square foot per day. This was above the estimated average daily solar radiation for this geographical area during the reporting period of 1191 Btu per square foot per day for a plane facing 15 degrees west of south with a tilt of 45 degrees to the horizontal. The average ambient temperature during the October 1978 through March 1979 period was 38°F which is the same as the long-term average for the period. The number of heating degree-days for the same period (based on a 65°F reference) was 806, as compared with the summation of the long-term averages of 810.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Similarly, if a day's average temperature was 80°F, then 15 cooling degree-days are accumulated. The total number of heating and cooling degree-days is summed monthly.

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the useful energy delivered to the loads (excluding losses in the system), both solar and auxiliary thermal energies. The portion of the total load provided by solar energy is defined as the solar fraction of the load.

TABLE 5-1. WEATHER CONDITIONS
M. F. SMITH ASSOCIATES

MONTH	DAILY INCIDENT SOLAR ENERGY PER UNIT AREA[1] (Btu/Ft^2)		AMBIENT TEMPERATURE (°F)		HEATING DEGREE-DAYS		COOLING DEGREE-DAYS	
	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE
OCT	1668	1380	54	55	345	327	0	0
NOV	985	1088	45	45	603	612	0	0
DEC	1060	951	36	33	885	984	0	0
JAN	862	992	32	30	1029	1091	0	0
(FEB)	1405	1252	22	30	1197	972	0	0
(MAR)	1314	1485	40	37	778	871	0	0
TOTAL					4837	4857	0	0
AVERAGE	1216	1191	38	38	806	810	0	0

[1] In collector array plane and azimuth, unless otherwise indicated in Section 5.1.

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The thermal performance of the M. F. Smith Associates solar energy system is presented in Table 5-2. This performance assessment is based on the 6-month period from October 1978 to March 1979. During the reporting period, a total of 36.86 million Btu of solar energy was collected and the total system load was 22.70 million Btu. The measured amount of solar energy delivered to the load subsystem(s) was 16.37 million Btu. The measured system solar fraction was 72 percent.

Figure 5-1 illustrates the flow of solar energy from the point of collection to the various points of consumption and loss for the reporting period. The numerical values account for the quantity of energy corresponding with the transport, operation, and function of each major element in the M. F. Smith Associates solar energy system.

Solar energy distribution flowcharts for each month of the reporting period are presented in Appendix D.

Table 5-3 summarizes solar energy distribution and provides a percentage breakdown. Appendix E contains the monthly solar energy percentage distributions.

The solar energy coefficient of performance (COP) is indicated in Table 5-4. The COP simply provides a numerical value for the relationship of solar energy collected or transported or used and the energy required to perform the transition. The greater the COP value, the more efficient the subsystem. The solar energy system at the M. F. Smith Associates site functioned at a weighted average COP value of 4.24 for the reporting period October 1978 through January 1979.

5.3 Subsystem Performance

The M. F. Smith Associates solar energy installation may be divided into three subsystems:

TABLE 5-2. SYSTEM THERMAL PERFORMANCE SUMMARY
M. F. SMITH ASSOCIATES

MONTH	SOLAR ENERGY COLLECTED (Million Btu)	SYSTEM LOAD (Million Btu)	SOLAR ENERGY USED (Million Btu)		SOLAR FRACTION (%)	
			EXPECTED	MEASURED	EXPECTED	MEASURED
OCT	7.30	0.36	N.A.	0.36	N.A.	100
NOV	4.11	3.84	N.A.	3.08	N.A.	80
DEC	5.59	8.86	N.A.	6.43	N.A.	73
JAN	4.71	9.64	N.A.	6.50	N.A.	67
(FEB)	6.72	*	N.A.	*	N.A.	*
(MAR)	8.43	*	N.A.	*	N.A.	*
TOTAL	36.86	22.70 (1)	N.A.	16.37 (1)		
AVERAGE	6.14	5.68 (1)	N.A.	4.09 (1)	N.A.	72

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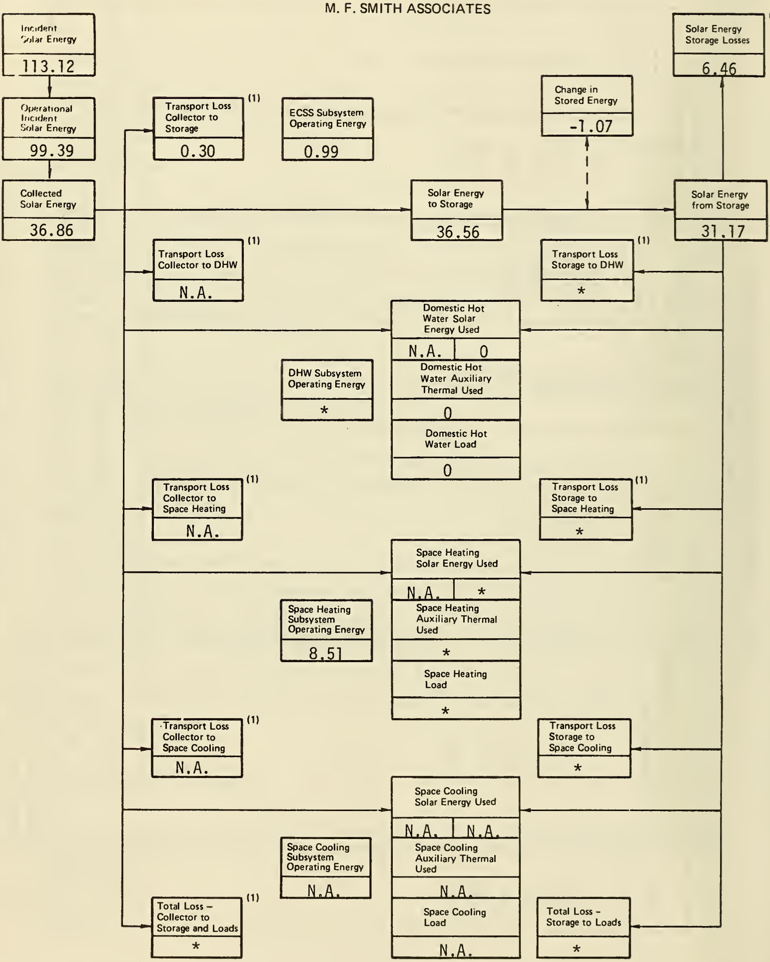
N.A. - Denotes not applicable data
* - Denotes unavailable data
(1) - Summation and averages based on 4-month data: October 1978 through January 1979

FIGURE 5-1. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - SUMMARY

M. F. SMITH ASSOCIATES



* Denotes Unavailable Data

N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

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TABLE 5-3. SOLAR ENERGY DISTRIBUTION - SUMMARY OCTOBER 1978 THROUGH MARCH 1979

M. F. SMITH ASSOCIATES

36.86 million Btu	100%	TOTAL SOLAR ENERGY COLLECTED
* million Btu	*%	SOLAR ENERGY TO LOADS
0 million Btu	0 %	SOLAR ENERGY TO DHW SUBSYSTEM
* million Btu	* %	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A. million Btu	- %	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
6.76 million Btu	18 %	SOLAR ENERGY LOSSES
6.46 million Btu	17 %	SOLAR ENERGY LOSS FROM STORAGE
* million Btu	%	SOLAR ENERGY LOSS IN TRANSPORT
0.30 million Btu	1 %	COLLECTOR TO STORAGE LOSS
N.A. million Btu	- %	COLLECTOR TO LOAD LOSS
N.A. million Btu	- %	COLLECTOR TO DHW LOSS
N.A. million Btu	- %	COLLECTOR TO SPACE HEATING LOSS
N.A. million Btu	- %	COLLECTOR TO SPACE COOLING LOSS
* million Btu	%	STORAGE TO LOAD LOSS
* million Btu	* %	STORAGE TO DHW LOSS
* million Btu	* %	STORAGE TO SPACE HEATING LOSS
N.A. million Btu	- %	STORAGE TO SPACE COOLING LOSS
-1.07 million Btu	-3 %	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data

N.A. - Denotes not applicable data

TABLE 5-4. SOLAR ENERGY SYSTEM COEFFICIENT OF PERFORMANCE
M. F. SMITH ASSOCIATES

MONTH	SOLAR ENERGY SYSTEM COP	COLLECTOR ARRAY SUBSYSTEM SOLAR COP	DOMESTIC HOT WATER SUBSYSTEM SOLAR COP	SPACE HEATING SUBSYSTEM SOLAR COP	SPACE COOLING SUBSYSTEM SOLAR COP
OCT	1.38	38.42	0	5.14	N.A.
NOV	4.60	34.25	0	5.60	N.A.
DEC	5.06	31.06	0	5.90	N.A.
JAN	4.06	36.23	0	4.25	N.A.
(FEB)	*	42.00	*	*	N.A.
(MAR)	*	40.14	*	*	N.A.
WEIGHTED AVERAGE	4.24 (1)	37.23	0 (1)	5.05 (1)	N.A.

S002

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) Summation and averages based on 4-month data: October 1978 through January 1979

1. Collector Array and Storage
2. Domestic Hot Water (DHW)
3. Space Heating

Each subsystem is evaluated and analyzed by the techniques defined in Section 4 to produce the monthly performance reports. This section presents the results of integrating the monthly data available on the three subsystems for the period October 1978 through March 1979.

5.3.1 Collector Array and Storage Subsystem

5.3.1.1 Collector Array

Collector array performance for the M. F. Smith Associates site is presented in Table 5-5. The total incident solar radiation on the collector array for the period October 1978 through March 1979 was 113.12 million Btu. During the period the collector loop was operating the total insolation amounted to 99.39 million Btu. The total collected solar energy for the period was 38.86 million Btu, resulting in a collector array efficiency of 33 percent, based on total incident insolation. Solar energy delivered from the collector array to storage was 36.56 million Btu.

Collector array efficiency has been computed from two bases. The first assumes that the efficiency is based upon all available solar energy. This approach makes the operation of the control system part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum; therefore, the energy is not collected. In this approach, collector array performance is described by comparing the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i$$

TABLE 5-5. COLLECTOR ARRAY PERFORMANCE
M. F. SMITH ASSOCIATES

MONTH	INCIDENT SOLAR ENERGY (Million Btu)	COLLECTED SOLAR ENERGY (Million Btu)	COLLECTOR ARRAY EFFICIENCY (%)	OPERATIONAL INCIDENT ENERGY (Million Btu)	OPERATIONAL COLLECTOR ARRAY EFFICIENCY (%)
OCT	26.48	7.30	28	23.03	32
NOV	15.13	4.11	27	12.85	32
DEC	16.82	5.59	33	14.70	38
JAN	13.69	4.71	34	11.96	39
(FEB)	20.14	6.72	33	17.81	38
(MAR)	20.86	8.43	40	19.04	44
TOTAL	113.12	36.86		99.39	
AVERAGE	18.85	6.14	33	16.57	37

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where: η_c = collector array efficiency

Q_s = collected solar energy

Q_i = incident solar energy

The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5-5.

The second approach assumes the efficiency is based upon the incident solar energy during the periods of collection only.

Evaluating collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yield operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s/(Q_{oi} \times \frac{A_p}{A_a})$$

where: Q_s = collected solar energy

Q_{oi} = operational incident energy

A_p = gross collector area (product of the number of collectors and the total envelope area of one unit)

A_a = gross collector array area (total area perpendicular to the solar flux vector, including all mounting, connecting and transport hardware)

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency" in Table 5-5. This latter efficiency

term is not the same as collector efficiency as represented by the ASHRAE Standard 9377 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady-state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are presented in Table 5-5.

5.3.1.2 Storage

Storage performance data for the M. F. Smith Associates site for the reporting period is shown in Table 5-6. Results of analysis of solar energy losses during transport and storage are shown in Table 5-7. This table contains an evaluation of solar energy transport losses as a fraction of energy transported to subsystems.

During the reporting period, total solar energy delivered to storage was 36.56 million Btu. There were 31.17 million Btu delivered from storage to the DHW and space heating subsystems. Energy loss from storage was 6.46 million Btu. This loss represented 21 percent of the energy delivered to storage. The storage efficiency was 82 percent: This is calculated as the ratio of the sum of the energy removed from storage and the change in stored energy, to the energy delivered to storage. The average storage temperature for the period was 69°F.

During December, January, and February energy was added to storage from the storage surroundings from passive and/or auxiliary heat sources. This resulted in a computed storage efficiency in excess of 100 percent. Storage subsystem performance is evaluated by comparison of energy to storage, energy from storage, and the change in stored energy. The ratio of the sum of energy from storage and the change in stored energy, to the energy to storage is

TABLE 5-6 STORAGE PERFORMANCE

M. F. SMITH ASSOCIATES

MONTH	ENERGY TO STORAGE (Million Btu)	ENERGY FROM STORAGE (Million Btu)	CHANGE IN STORED ENERGY (Million Btu)	STORAGE EFFICIENCY (%)	STORAGE AVERAGE TEMPERATURE (°F)	EFFECTIVE STORAGE HEAT LOSS COEFFICIENT (Btu/Hr -- °F)
OCT	7.00	0.46	-0.09	5	113	N.A.
NOV	4.11	3.08	-1.42	40	90	N.A.
DEC	5.59	6.43	-0.07	113 (1)	55	N.A.
JAN	4.71	6.50	-0.08	136 (1)	46	N.A.
(FEB)	6.72	7.94	0	118 (1)	48	N.A.
(MAR)	8.43	6.76	0.59	87	60	N.A.
TOTAL	36.56	31.17	-1.07			
AVERAGE	6.09	5.20	-0.18	82	69	N.A.

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) - Energy from storage surroundings was added to storage during the month.

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TABLE 5-7. SOLAR ENERGY LOSSES – STORAGE AND TRANSPORT
M. F. SMITH ASSOCIATES

	MONTH							
	OCT	NOV	DEC	JAN	FEB	MAR		TOTAL
1. SOLAR ENERGY (SE) COLLECTED MINUS SE DIRECTLY TO LOADS (million Btu)	7.30	4.11	5.59	4.71	6.72	8.43		36.86
2. SE TO STORAGE (million Btu)	7.00	4.11	5.59	4.71	6.72	8.43		36.56
3. LOSS – COLLECTOR TO STORAGE (%) $\frac{1-2}{1}$	4	0	0	0	0	0		1
4. CHANGE IN STORED ENERGY (million Btu)	-0.09	-1.42	-0.07	-0.08	0	0.59		-1.07
5. SOLAR ENERGY – STORAGE TO DHW SUBSYSTEM (million Btu)	0	0	0	0	*	*		0
6. SOLAR ENERGY – STORAGE TO SPACE HEATING SUBSYSTEM (million Btu)	0.46	3.08	6.43	6.50	*	*		*
7. SOLAR ENERGY – STORAGE TO SPACE COOLING SUBSYSTEM (million Btu)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.		N.A.
8. LOSS FROM STORAGE (%) $\frac{2-(4+5+6+7)}{2}$	95	60	-14	-36	*	*		*
9. HOT WATER SOLAR ENERGY (HWSE) FROM STORAGE (million Btu)	0	0	0	0	*	*		0
10. LOSS – STORAGE TO HWSE (%) $\frac{5-9}{5}$	0	0	0	0	*	*		0
11. HEATING SOLAR ENERGY (HSE) FROM STORAGE (million Btu)	0.36	3.08	6.93	6.50	*	*		*
12. LOSS – STORAGE TO HSE (%) $\frac{6-11}{6}$	22	0	0	0	*	*		*

S002

* - Denotes unavailable data
N.A. - Denotes not applicable data

defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si}$$

where:

ΔQ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value)

Q_{so} = energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium

Q_{si} = energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium

5.3.2 Domestic Hot Water (DHW) Subsystem

The DHW subsystem performance for the M. F. Smith Associates site for the reporting period is shown in Table 5-8. There was no hot water load during the first four months of the reporting period. During February and March an undetermined amount of solar and/or auxiliary electrical energy was used to satisfy a hot water load of 1.51 million Btu.

5.3.3 Space Heating Subsystem

The space heating subsystem performance for the M. F. Smith Associates site for the first four months of the reporting period is shown in Table 5-9. The space heating subsystem consumed 16.37 million Btu of solar energy and 6.33 million Btu of auxiliary electrical energy to satisfy a space heating load of 22.70 million Btu. The solar fraction of this load was 72 percent.

TABLE 5-8. DOMESTIC HOT WATER SUBSYSTEM PERFORMANCE
M. F. SMITH ASSOCIATES

MONTH	DOMESTIC HOT WATER LOAD (Million Btu)	ENERGY CONSUMED (Million Btu)				SOLAR FRACTION (%)
		SOLAR	AUXILIARY THERMAL	AUXILIARY		
				ELECTRICAL	FOSSIL	
OCT	0	0	0	0	0	0
NOV	0	0	0	0	0	0
DEC	0	0	0	0	0	0
JAN	0	0	0	0	0	0
(FEB)	0.42	*	*	*	*	*
(MAR)	1.09	*	*	*	*	*
TOTAL	1.51	*	*	*	*	
AVERAGE	0.25	*	*	*	*	

* - Denotes unavailable data

S002

TABLE 5-9. SPACE HEATING SUBSYSTEM PERFORMANCE
M. F. SMITH ASSOCIATES

MONTH	SPACE HEATING LOAD (Million Btu)	ENERGY CONSUMED (Million Btu)				SOLAR FRACTION (%)
		SOLAR	AUXILIARY THERMAL	AUXILIARY		
				ELECTRICAL	FOSSIL	
OCT	0.36	0.36	0	0		100
NOV	3.84	3.08	0.76	0.76		80
DEC	8.86	6.43	2.43	2.43		73
JAN	9.64	6.50	3.14	3.14		67
(FEB)	*	*	*	*		*
(MAR)	*	*	*	*		*
TOTAL	(1) 22.70	16.37	6.33	6.33		
AVERAGE	(1) 5.68	4.09	1.58	1.58		72

S002

* - Denotes unavailable data

(1) Summation and averages based on 4—month data: October 1978 through January 1979

TABLE 5-10 OPERATING ENERGY
M. F. SMITH ASSOCIATES

MONTH	ENERGY COLLECTION AND STORAGE OPERATING ENERGY (Million Btu)	DOMESTIC HOT WATER OPERATING ENERGY (Million Btu)	SPACE HEATING OPERATING ENERGY (Million Btu)	SPACE COOLING OPERATING ENERGY (Million Btu)	TOTAL SYSTEM OPERATING ENERGY (Million Btu)
OCT	0.19	0.02	0.07	N.A.	0.28
NOV	0.12	0.03	0.69	N.A.	0.84
DEC	0.18	0	1.49	N.A.	1.67
JAN	0.13	0	2.28	N.A.	2.41
(FEB)	0.16	*	2.27	N.A.	*
(MAR)	0.21	*	1.71	N.A.	*
TOTAL	0.99	0.05(1)	8.51	N.A.	5.20(1)
AVERAGE	0.17	0.01(1)	1.42	N.A.	1.30(1)

S002

*   - Denotes unavailable data
N.A. - Denotes not applicable data
(1) Summation and averages based on 4-month data: October 1978 through January 1979

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction.

5.4 Operating Energy

Measured values of the M. F. Smith Associates solar energy system and subsystem operating energy for the reporting period are presented in Table 5-10. A total of 5.20 million Btu of operating energy was consumed by the entire system during the first four months of the reporting period.

Operating energy for a solar energy system is defined as the amount of electrical energy required to support the subsystems without affecting their thermal state.

Total system operating energy for the M. F. Smith Associates site is the energy required to support the energy collection and storage subsystem (ECSS), DHW subsystem, and the space heating subsystem. With reference to the system schematic (Figure 3-1), the ECSS operating energy includes pumps P1 and P2 (EP100). The DHW subsystem operating energy consists of pump P4 (EP301). The space heating subsystem operating energy consists of pump P3 (EP401) and heat pump EP402.

5.5 Energy Savings

Energy savings for the M F. Smith Associates site for the reporting period are presented in Table 5-11. For the first 4 months of the period the total savings on electrical energy were 4.78 million Btu, for a monthly average of 1.20 million Btu. An electrical energy expense of 0.05 million Btu was incurred during the reporting period for the operation of solar energy transportation pumps.

TABLE 5-11 ENERGY SAVINGS
M. F. SMITH ASSOCIATES

MONTH	SOLAR ENERGY USED (Million Btu)	SOLAR ENERGY SAVINGS ATTRIBUTED TO (Million Btu)						SOLAR OPERATING ENERGY (Million Btu)	ENERGY SAVINGS (Million Btu)	
		SPACE HEATING		DOMESTIC HOT WATER		SPACE COOLING				
		ELECTRICAL	FOSSIL FUEL	ELECTRICAL	FOSSIL FUEL	ELECTRICAL	FOSSIL FUEL		ELECTRICAL	FOSSIL FUEL
OCT	0.36	0.32	N.A.	-0.02	N.A.	N.A.	N.A.	0.26	0.11	N.A.
NOV	3.08	1.46	N.A.	-0.03	N.A.	N.A.	N.A.	0.67	1.33	N.A.
DEC	6.43	2.56	N.A.	0	N.A.	N.A.	N.A.	1.27	2.38	N.A.
JAN	6.50	1.09	N.A.	0	N.A.	N.A.	N.A.	1.66	0.96	N.A.
(FEB)	*	*	N.A.	*	N.A.	N.A.	N.A.	*	*	N.A.
(MAR)	*	*	N.A.	*	N.A.	N.A.	N.A.	*	*	N.A.
TOTAL	(1) 16.37	5.43	N.A.	-0.05	N.A.	N.A.	N.A.	3.86	4.78	N.A.
AVERAGE	(1) 4.09	1.36	N.A.	-0.01	N.A.	N.A.	N.A.	0.97	1.20	N.A.

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) - Summation and averages based on 4-month data: October 1978 through January 1979

S002

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution to determine net savings.

6. REFERENCES

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4. Mears, J. C. Reference Monthly Environmental Data for Systems in the National Solar Data Network. Department of Energy report SOLAR/0019-79/36. Washington, D.C., 1979.

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7.# Monthly Performance Report, M. F. Smith Associates, SOLAR/1056-78/10, Department of Energy, Washington, D.C., (October 1978).

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10.# Monthly Performance Report, M. F. Smith Associates, SOLAR/1056-79/01, Department of Energy, Washington, D.C., (January 1979).

#Copies of these reports may be obtained from Technical Information Center P. O. Box 62, Oak Ridge, Tennessee 37830.

APPENDIX A

DEFINITIONS OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady-state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary energy supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow into and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to directly affect the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY FOSSIL FUEL (HWAF) is the amount of fossil fuel energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- FOSSIL FUEL SAVINGS (HWSVF) is the estimated difference between the fossil fuel energy requirements of the alternative conventional system (carrying the full load) and the actual fossil fuel energy requirements of the subsystem.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow into the subsystem. The average building temperature is tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to directly affect the thermal state of the system.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS

M. F. SMITH ASSOCIATES

INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each sensor every 320 seconds. This data is then mathematically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this site.

Data samples from the system measurements are integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu per square foot per hour, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document was prepared by an interagency committee of the Government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each integration process, therfore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED TO GENERATE MONTHLY PERFORMANCE VALUES

NOTE: SENSOR IDENTIFICATION (MEASUREMENT) NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

AVERAGE AMBIENT TEMPERATURE (°F)

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times \Sigma\ [(T600 + T601)/2] \times \Delta\tau$$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$$

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/lb_m - °F)

$$HRF = 0.24 + 0.444 \times HR$$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$$SECA = \Sigma\ [M101 \times (H(T151) - H(T101) + M100\ (H(T150) - H(T100))]\ \Delta\tau$$

WHERE H(TXXX) IS A FUNCTION WHICH CALCULATES THE ENTHALPY OF THE TRANSPORT MEDIUM

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = \Sigma\ [M101 \times (H(T153) - H(T103)) + M100 \times (H(T152) - HT(102))]\ \Delta\tau$$

SOLAR ENERGY FROM STORAGE (BTU)

$$STEO = \Sigma\ [M300 \times (H(T350) - H(T300)) + M400 \times (H(T400) - H(T450))]\ \Delta\tau$$

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TST = (1/60) \times \Sigma\ [T200 + T201 + T202)/3] \times \Delta\tau$$

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS

$$CSEO = \Sigma\ [M300 \times (H(T350) - H(T300)) + M400 \times (H(T401) - H(T451))]\ \Delta\tau$$

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma\ EP100 \times \Delta\tau$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY

$$HOPE = 56.8833\ (EP401 + 0.2\ EP402)$$

WHEN SYSTEM USES SOLAR ASSISTED HEAT PUMP

$$HOPE = 56.8833 \times EP401 + EP402$$

WHEN SYSTEM USES HYDRONIC COILS

SOLAR ENERGY TO SPACE HEATING

$$HSE = HPSE = \Sigma\ [M400 \times ((HT400) - H(T450)) - EP400 \times 56.8833] \times \Delta\tau \times H\ RATIO$$

DURING HEAT PUMP OPERATION

WHERE $HRATIO = \dfrac{HPHL}{HPHL + HPHWL}$ AND

$$HPHL = \Sigma\ [M401 \times HRF \times (T452 - T402)] \times \Delta\tau$$

DURING HEAT PUMP OPERATION

AND

$$HPHWL = \Sigma\ [(M301 + M300) \times (H(T351) - H(T301))] \times \Delta\tau$$

$$HSE = \Sigma\ [M400 \times (H(T400) - H(T450))] \times \Delta\tau$$

DURING HYDRONIC COIL OPERATION

SPACE HEATING SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$HAE = (HPAE1 + HPAE2) \times HRATIO$

WHERE $HPAE1 = 56.8833 \times EP400 \times \Delta\tau$

AND

$HPAE2 = 56.8833 \times 0.7 \times EP402 \times \Delta\tau$

SPACE HEATING SUBSYSTEM AUXILIARY THERMAL ENERGY (BTU)

$HAT = HAE$

SPACE HEATING SUBSYSTEM LOAD (BTU)

$HL = HAT + HSE$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$HSFR = 100 \times HSE/HL$

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

$HSVE = CSE02/HPCOP + CSE03 - HOPE1$

WHERE $CSE02 = \Sigma\ [M400 \times (H(T401) - H(T451))] \times \Delta\tau$

WHEN HEAT PUMP IS OPERATING

$CSE03 = \Sigma\ [M400 \times (H(T401) - H(T451))] \times \Delta\tau$

WHEN USING HYDRONIC COIL

$HOPE1 = 56.8833 \times \Sigma\ EP401 \times \Delta\tau$

HOT WATER CONSUMED (GALLONS)

$HWCSM = \Sigma\ W300 \times \Delta\tau$

SOLAR ENERGY TO HOT WATER (BTU)

$HWSE = HWSE1 + HPSE \times (1 - HRATIO)$

WHERE $HWSE1 = \Sigma\ [M300 \times (H(T350) - H(T300))] \times \Delta\tau$

HPSE AND HRATIO AS DEFINED PREVIOUSLY

HOT WATER SUBSYSTEM OPERATION ENERGY (BTU)

$HWOPE = 56.8833\ \Sigma\ EP301 \times \Delta\tau$

HOT WATER AUXILIARY ELECTRIC ENERGY (BTU)

$HWAE = HWAE1 + (HPAE1 + HPAE2) \times (1 - HRATIO)$

WHERE $HWAE1 = 56.8833 \times \Sigma\ EP300 \times \Delta\tau$

$HPAE1 = 56.8833 \times \Sigma\ EP400 \times \Delta\tau$ AND

$HPAE2 - 0.7 \times 56.8833 \times \Sigma\ EP402 \times \Delta\tau$

HRATIO IS AS PREVIOUSLY DEFINED

HOT WATER AUXILIARY THERMAL ENERGY (BTU)

$HWAT - HWAE$

HOT WATER LOAD (BTU)

$HWL = \Sigma\ [M300 \times (H(T353) - H(T300))] \times \Delta\tau$

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = FRACTION OF DELIVERED HOT WATER LOAD DERIVED FROM SOLAR SOURCES AFTER PRO-RATING STORAGE LOSSES TO SOLAR AND AUXILIARY SOURCES

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

$HWSVE = HWSE1 - HWOPE$

SERVICE SUPPLY WATER TEMPERATURE (°F)

$TSW = (1/60) \times \Sigma\ T300 \times \Delta\tau$

WHEN WATER IS BEING DRAWN

SERVICE HOT WATER TEMPERATURE (°F)

$THW = (1/60) \times \Sigma\ T352 \times \Delta\tau$

WHEN WATER IS BEING DRAWN

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$SEA = CLAREA \times SE$

COLLECTED SOLAR ENERGY (BTU)

$SEC = SECA/CLAREA$

COLLECTOR ARRAY EFFICIENCY

CAREL = SECA/SEA

CHANGE IN STORED ENERGY (BTU)

$STECH = STECH1 - STECH_p$

WHERE THE SUBSCRIPT $_p$ REFERS TO A PRIOR REFERENCE VALUE

STORAGE EFFICIENCY

STEFF = (STECH + STEO)/STEI

SOLAR ENERGY TO LOAD SUBSYSTEM (BTU)

SEL = HWSE + HSE

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

SYSTEM LOAD (BTU)

SYSL = HWL + HL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT

SFR = (HWSFR x HWL + HSFR x HL)/SYSL

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE + HAE

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HWOPE + HOPE + CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = AXE + SYSOPE + SECA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE + HSVE - CSOPE

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/((AXE + SYSOPE) x 3.33)

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

This appendix contains a table which lists the long-term average weather conditions for each month of the year for this site.

SITE: M.F. SMITH 160. LOCATION: JAMESTOWN RI

ANALYST: D. FONTAINE FDRIVE NO.: 27.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 15.00 (DEGREES)

LATITUDE: 41.52 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1245.	557.	0.44723	1.781	992.	1091	0	30.
FEB	1715.	833.	0.48591	1.503	1252.	972	0	30.
MAR	2331.	1202.	0.51560	1.235	1435.	871	0	37.
APR	2983.	1456.	0.48824	1.012	1474.	560	0	46.
MAY	3450.	1714.	0.49694	0.886	1519.	301	4	55.
JUN	3643.	1895.	0.52021	0.835	1582.	58	53	65.
JUL	3542.	1844.	0.52047	0.857	1580.	4	188	71.
AUG	3160.	1637.	0.51810	0.957	1567.	10	160	70.
SEP	2563.	1357.	0.52929	1.145	1554.	86	69	64.
OCT	1893.	973.	0.51412	1.418	1380.	327	0	55.
NOV	1354.	634.	0.46852	1.715	1088.	612	0	45.
DEC	1118.	501.	0.44857	1.897	951.	984	0	33.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

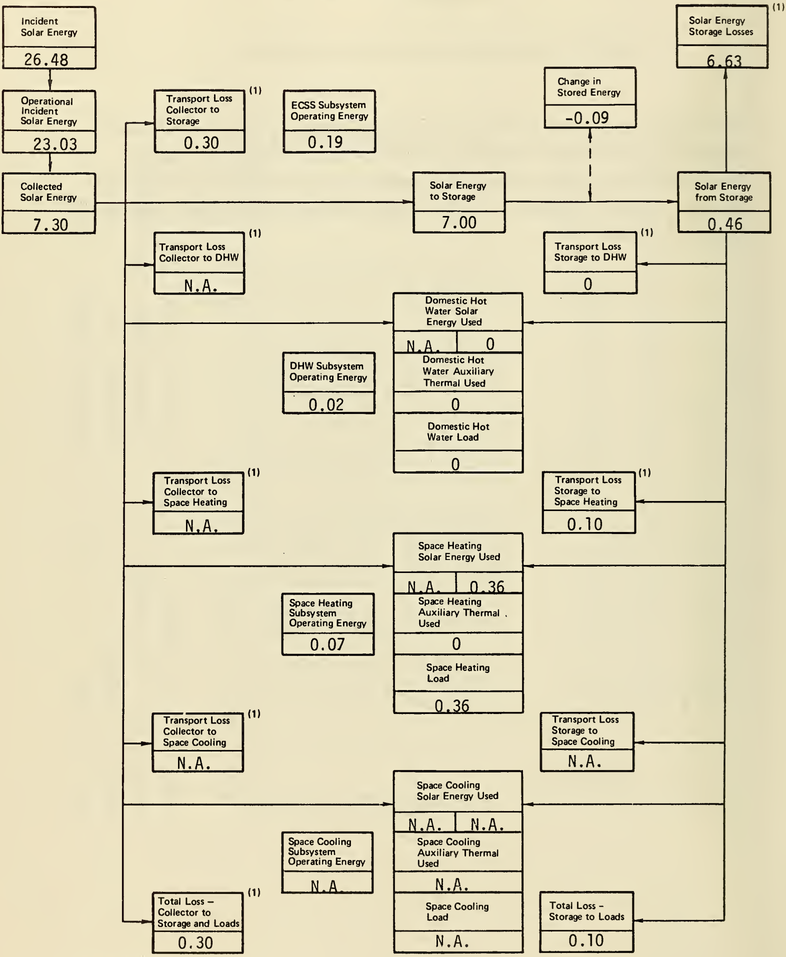
APPENDIX D

MONTHLY SOLAR ENERGY DISTRIBUTION FLOWCHARTS

The flowcharts in this appendix depict the quantity of solar energy corresponding to each major component or characteristic of the M. F. Smith Associates solar energy system for 6 months of the reporting period. Each monthly flowchart represents a solar energy balance as the total input equals the total output.

FIGURE D-1. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - OCTOBER 1978

M. F. SMITH ASSOCIATES



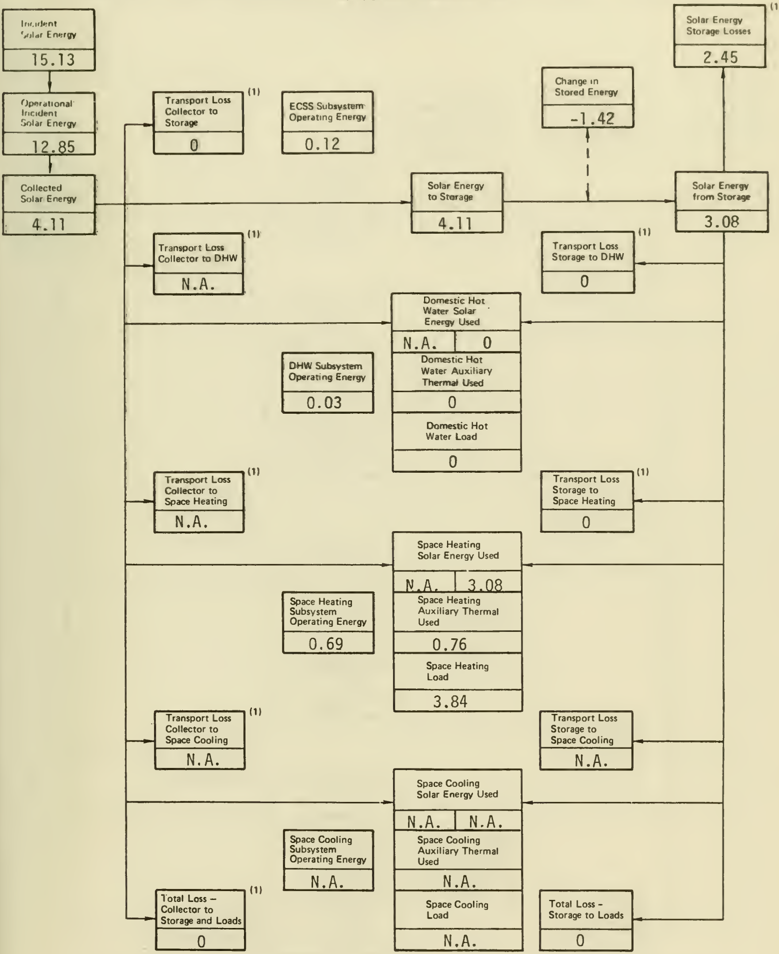
* Denotes Unavailable Data

N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

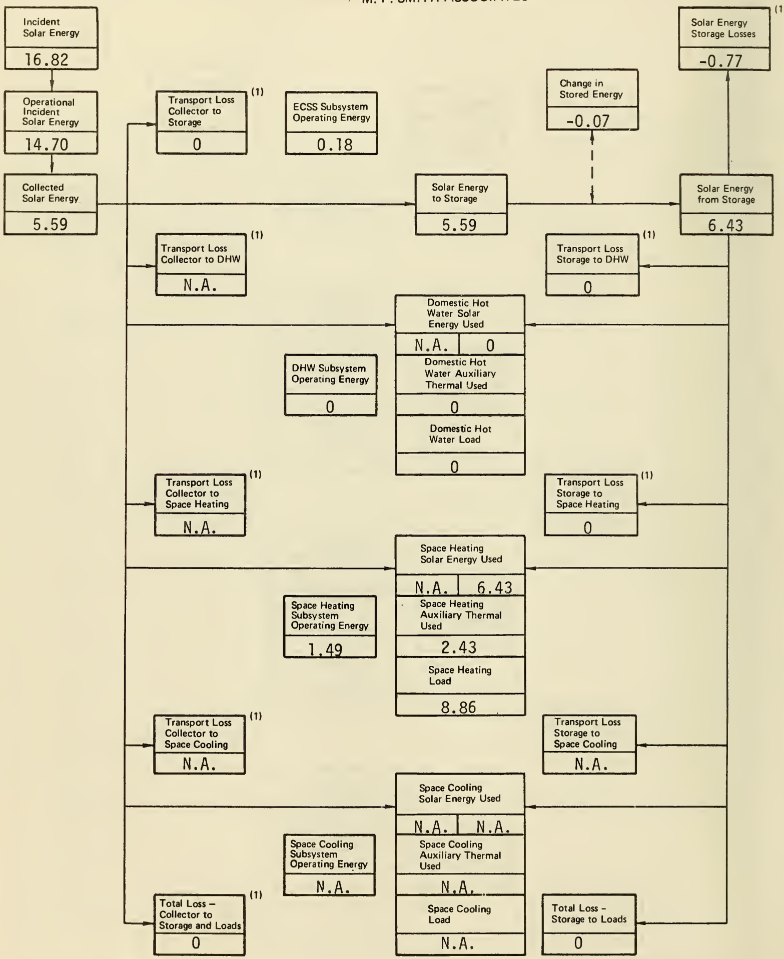
FIGURE D-2. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - NOVEMBER 1978
M. F. SMITH ASSOCIATES



* Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

FIGURE D-3. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - DECEMBER 1978
M. F. SMITH ASSOCIATES

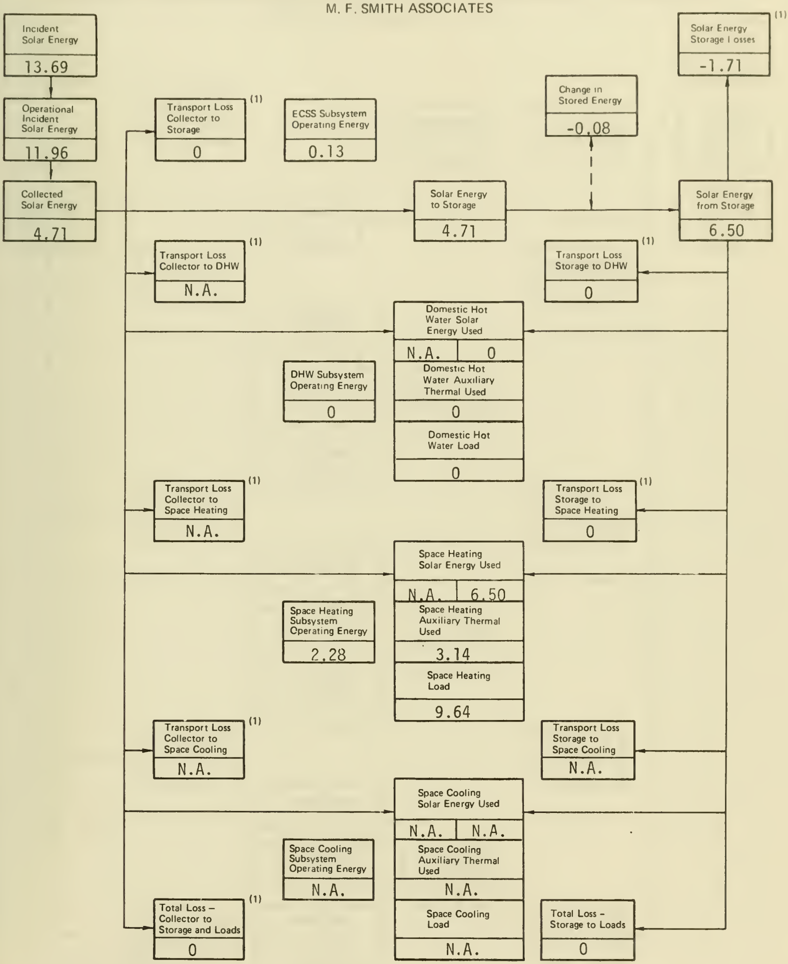


* Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

FIGURE D-4. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - JANUARY 1979

M. F. SMITH ASSOCIATES



* Denotes Unavailable Data

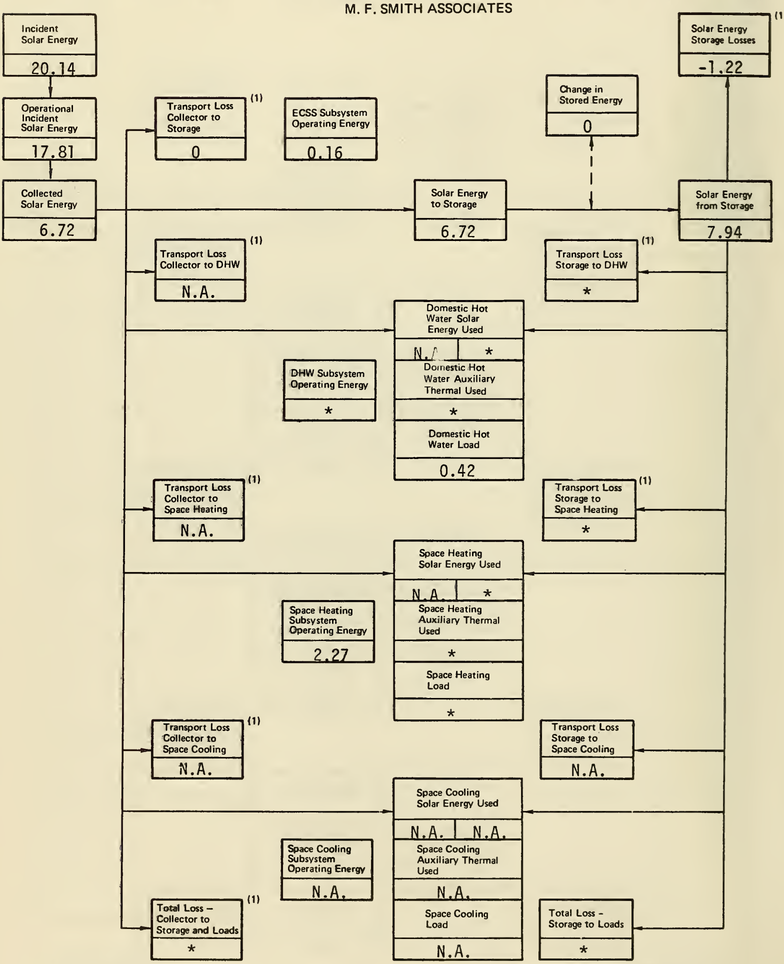
N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

FIGURE D-5. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - (FEBRUARY 1979)

M. F. SMITH ASSOCIATES



* Denotes Unavailable Data

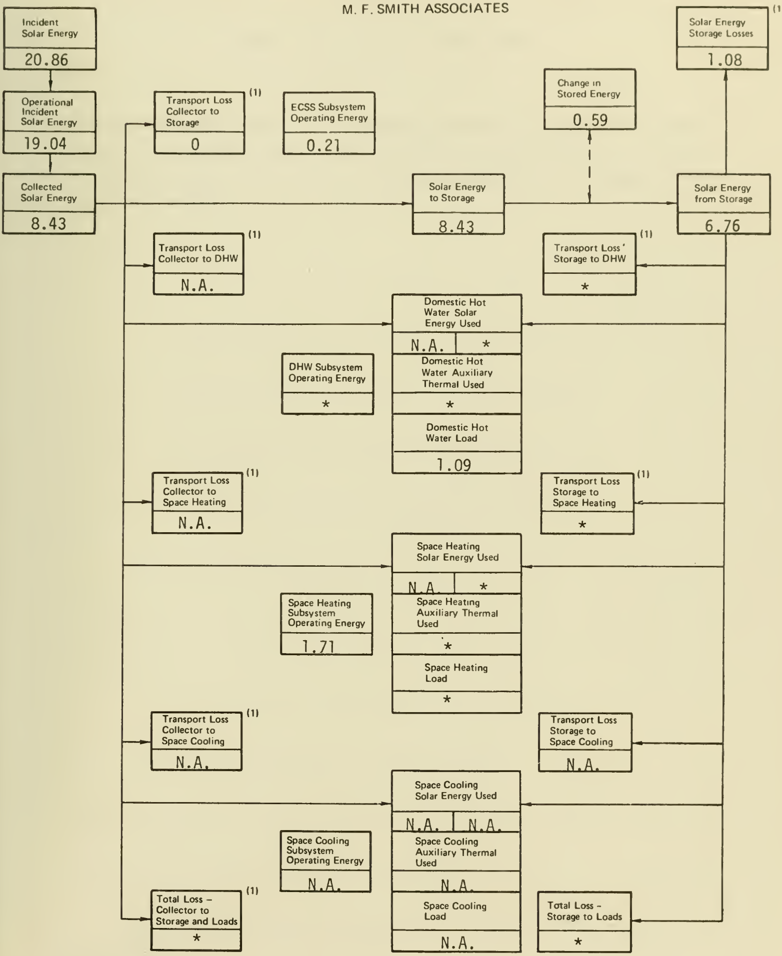
N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

FIGURE D-6. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART -(MARCH 1979)

M. F. SMITH ASSOCIATES



* Denotes Unavailable Data

N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

APPENDIX E

MONTHLY SOLAR ENERGY DISTRIBUTIONS

The data tables provided in this appendix present an indication of solar energy distribution, intentional and unintentional, in the M. F. Smith Associates solar energy system. Tables are provided for 6 months of the reporting period.

TABLE E-1. SOLAR ENERGY DISTRIBUTION - OCTOBER 1978
M. F. SMITH ASSOCIATES

Million Btu	%	
7.30	100%	TOTAL SOLAR ENERGY COLLECTED
0.36	5 %	SOLAR ENERGY TO LOADS
0	0 %	SOLAR ENERGY TO DHW SUBSYSTEM
0.36	5 %	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	0 %	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
7.03	96 %	SOLAR ENERGY LOSSES
6.63	91 %	SOLAR ENERGY LOSS FROM STORAGE
0.40	5 %	SOLAR ENERGY LOSS IN TRANSPORT
0.30	4 %	COLLECTOR TO STORAGE LOSS
N.A.	%	COLLECTOR TO LOAD LOSS
N.A.	%	COLLECTOR TO DHW LOSS
N.A.	%	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	COLLECTOR TO SPACE COOLING LOSS
0.10	1 %	STORAGE TO LOAD LOSS
N.A.	%	STORAGE TO DHW LOSS
0.10	1 %	STORAGE TO SPACE HEATING LOSS
N.A.	%	STORAGE TO SPACE COOLING LOSS
-0.09	-1 %	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data

TABLE E-2. SOLAR ENERGY DISTRIBUTION - NOVEMBER 1978
M. F. SMITH ASSOCIATES

4.11	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
3.08	75 %	million Btu	SOLAR ENERGY TO LOADS
0	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
3.08	75 %	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
2.45	60 %	million Btu	SOLAR ENERGY LOSSES
2.45	60 %	million Btu	SOLAR ENERGY LOSS FROM STORAGE
*	* %	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
*	* %	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
*	* %	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
*	* %	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
-1.42	-35 %	million Btu	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data

TABLE E-3. SOLAR ENERGY DISTRIBUTION - DECEMBER 1978
M. F. SMITH ASSOCIATES

5.59	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
6.43	%	million Btu	SOLAR ENERGY TO LOADS
0	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
6.43	%	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
-0.77 (1)	-14 %	million Btu	SOLAR ENERGY LOSSES
-0.77	014 %	million Btu	SOLAR ENERGY LOSS FROM STORAGE
*	* %	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
*	* %	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
*	%	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
*	%	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
-0.07	-1 %	million Btu	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) Transport losses assumed insignificant

TABLE E-4. SOLAR ENERGY DISTRIBUTION - JANUARY 1979
M. F. SMITH ASSOCIATES

4.71	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
6.50	138 %	million Btu	SOLAR ENERGY TO LOADS
0	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
6.50	138 %	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
-1.71	-36 %	million Btu	SOLAR ENERGY LOSSES
-1.71	-36 %	million Btu	SOLAR ENERGY LOSS FROM STORAGE
*	* %	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
*	* %	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
*	* %	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
*	* %	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
-0.08	-2 %	million Btu	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data

TABLE E-5. SOLAR ENERGY DISTRIBUTION -(FEBRUARY 1979)
M. F. SMITH ASSOCIATES

6.72 million Btu	100%	TOTAL SOLAR ENERGY COLLECTED
* million Btu	* %	SOLAR ENERGY TO LOADS
* million Btu	* %	SOLAR ENERGY TO DHW SUBSYSTEM
* million Btu	%	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A. million Btu	%	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
-1.22 million Btu	-18 %	SOLAR ENERGY LOSSES
-1.22 million Btu	18 %	SOLAR ENERGY LOSS FROM STORAGE
* million Btu	* %	SOLAR ENERGY LOSS IN TRANSPORT
* million Btu	* %	COLLECTOR TO STORAGE LOSS
N.A. million Btu	%	COLLECTOR TO LOAD LOSS
N.A. million Btu	%	COLLECTOR TO DHW LOSS
N.A. million Btu	%	COLLECTOR TO SPACE HEATING LOSS
N.A. million Btu	%	COLLECTOR TO SPACE COOLING LOSS
* million Btu	* %	STORAGE TO LOAD LOSS
* million Btu	* %	STORAGE TO DHW LOSS
* million Btu	* %	STORAGE TO SPACE HEATING LOSS
N.A. million Btu	%	STORAGE TO SPACE COOLING LOSS
million Btu	%	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data

TABLE E-6. SOLAR ENERGY DISTRIBUTION -(MARCH 1979)
M. F. SMITH ASSOCIATES

8.43 million Btu	100%	TOTAL SOLAR ENERGY COLLECTED
* million Btu	* %	SOLAR ENERGY TO LOADS
* million Btu	* %	SOLAR ENERGY TO DHW SUBSYSTEM
* million Btu	* %	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A. million Btu	%	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
1.08 million Btu	13 %	SOLAR ENERGY LOSSES
1.08 million Btu	13 %	SOLAR ENERGY LOSS FROM STORAGE
* million Btu	* %	SOLAR ENERGY LOSS IN TRANSPORT
* million Btu	* %	COLLECTOR TO STORAGE LOSS
N.A. million Btu	%	COLLECTOR TO LOAD LOSS
N.A. million Btu	%	COLLECTOR TO DHW LOSS
N.A. million Btu	%	COLLECTOR TO SPACE HEATING LOSS
N.A. million Btu	%	COLLECTOR TO SPACE COOLING LOSS
* million Btu	* %	STORAGE TO LOAD LOSS
* million Btu	* %	STORAGE TO DHW LOSS
* million Btu	* %	STORAGE TO SPACE HEATING LOSS
N.A. million Btu	%	STORAGE TO SPACE COOLING LOSS
0.59 million Btu	7 %	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data